Lithography Basics

- Resolution
- Placement
- Throughput
- Cost

Requirements for Advanced IC Lithography

Arbitrary geometries with:

- Critical Dimension (CD) ↘ 130 nm — 15 nm (speed)
- Overlay: CD/3 (circuit density)
- CD control: CD/10 (speed/power/complexity)

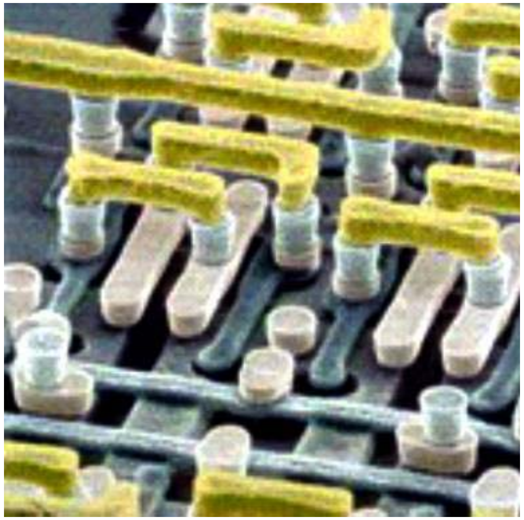


Image courtesy of IBM

- Perfection
  - 2003: 2×10^{10} pixels
  - 2012: 4×10^{11} pixels
- Cost-of-ownership
- Availability (Timing)

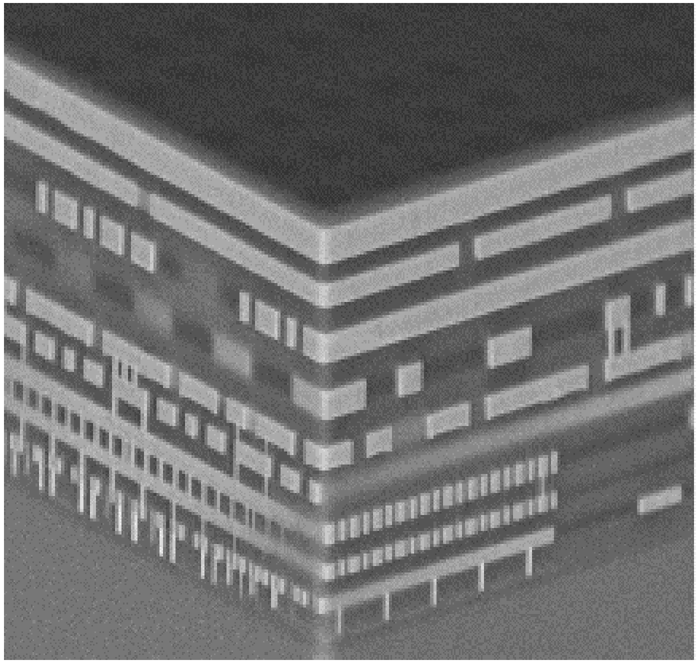
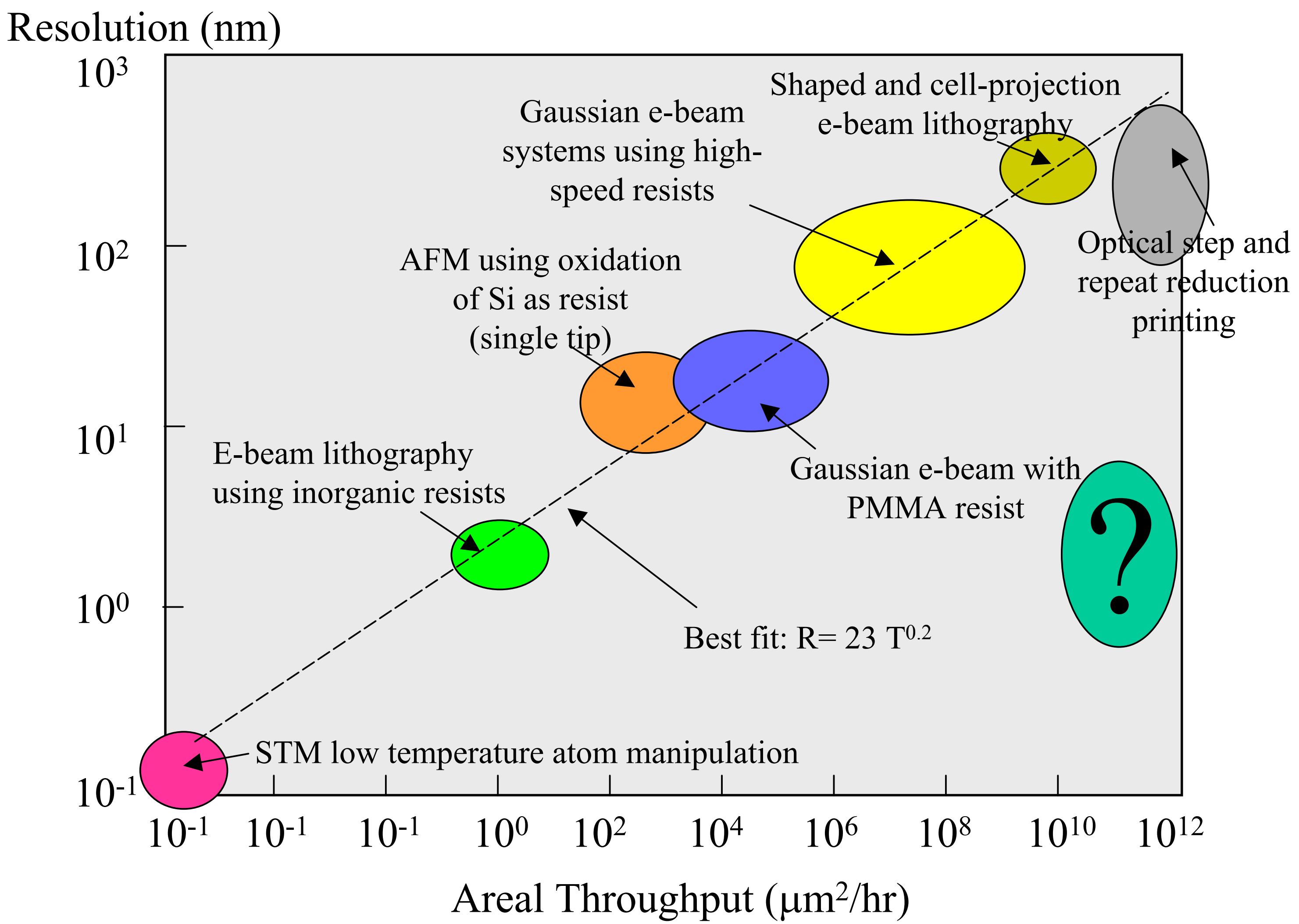


Image courtesy of AMD

Patterning Technologies

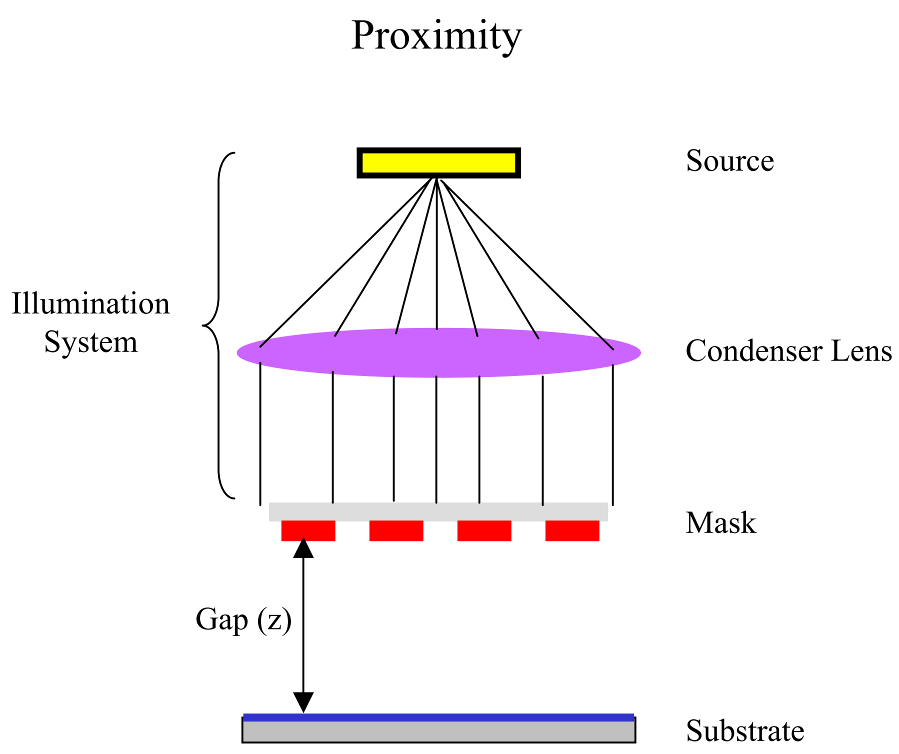
- Serial
  - Laser writers
    - Laser printers
    - Digital micromirror arrays
  - Focused Ion Beam (FIB)
  - Electron Beam
- Multiple Serial
  - Electron-Beam Microcolumns
  - Zone Plate Array Lithography
  - Scanning Proximal Probe
- Other
  - Interferometric/Holographic
  - Neutral Atom
- Parallel
  - Optical
  - X-ray
    - Proximity
    - LIGA
  - Ion Beam
  - Extreme Ultraviolet (EUV)
  - Electron Beam
  - Direct Transfer
    - Imprint
    - Step&Flash
    - Micro-Contact
    - Ink jet

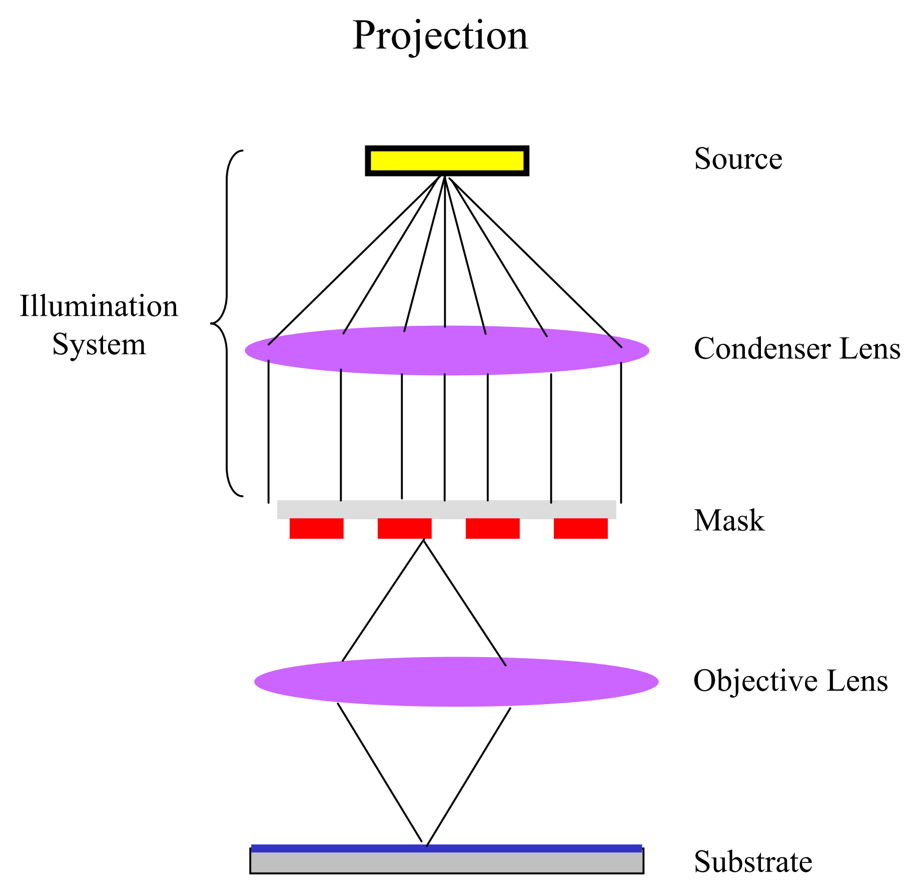
Resolution vs Throughput



After D.M Tennant and C.R. Marrian, JVST 2003

Proximity & Projection

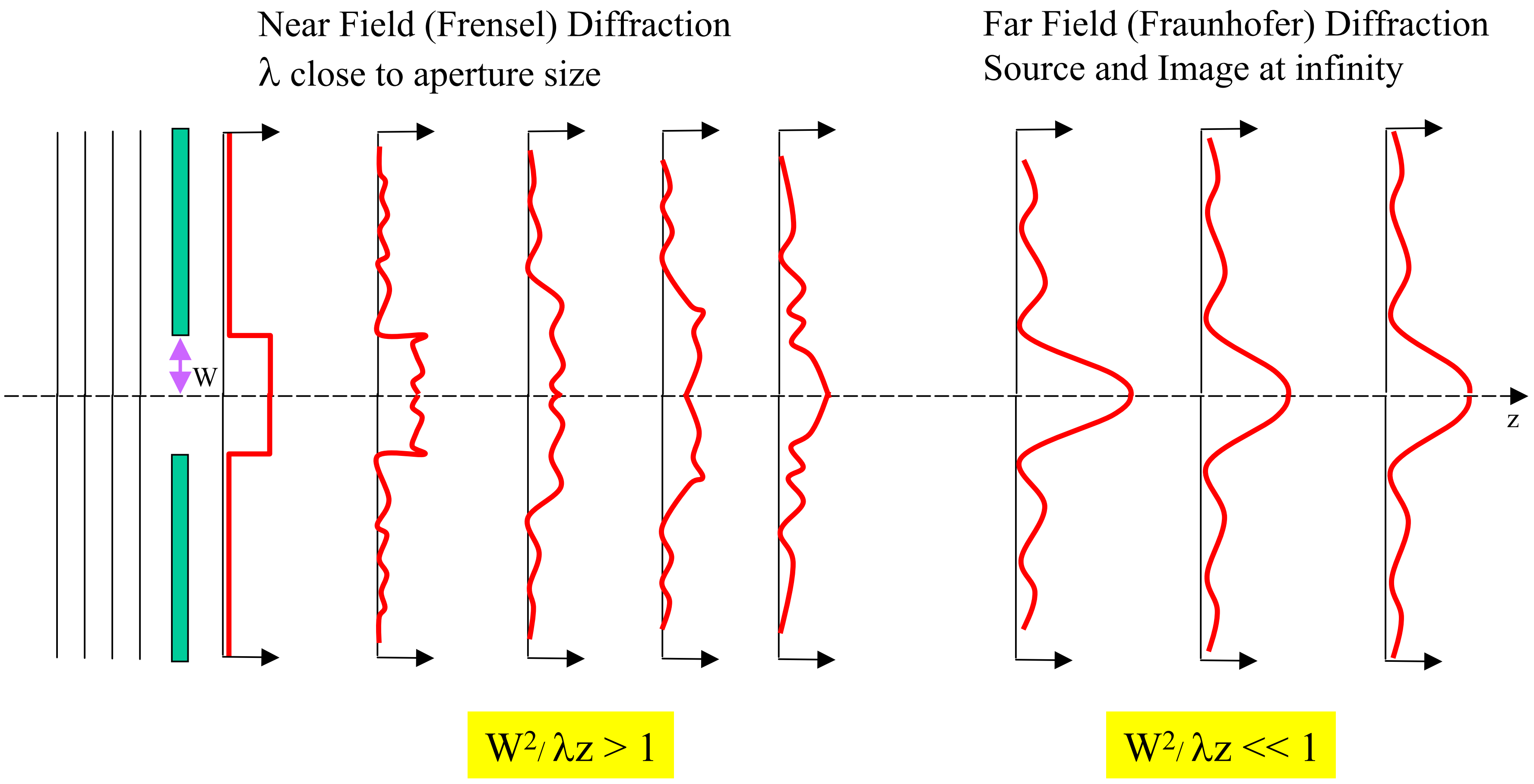




- Simple
- Resolution controlled by λ and z
- Mask issues: 1x, damage

- Complex
- Resolution affected by λ, NA
- Mask 4x, protected

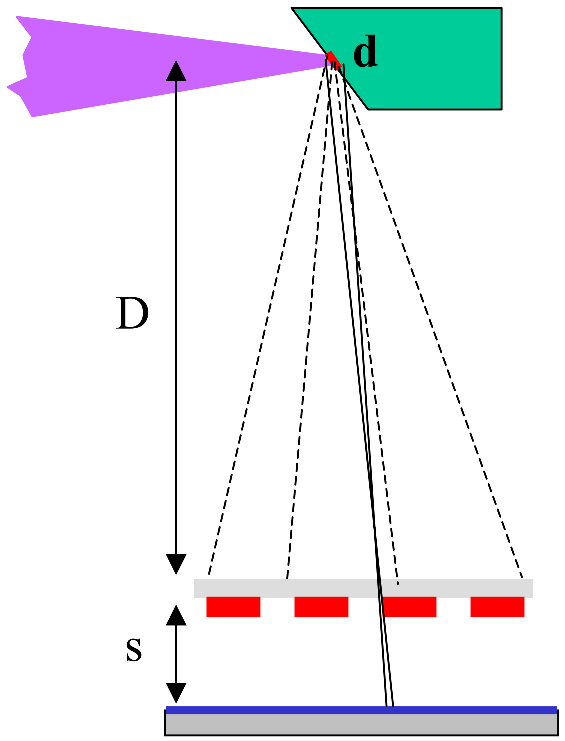
Fresnel & Fraunhofer Diffraction

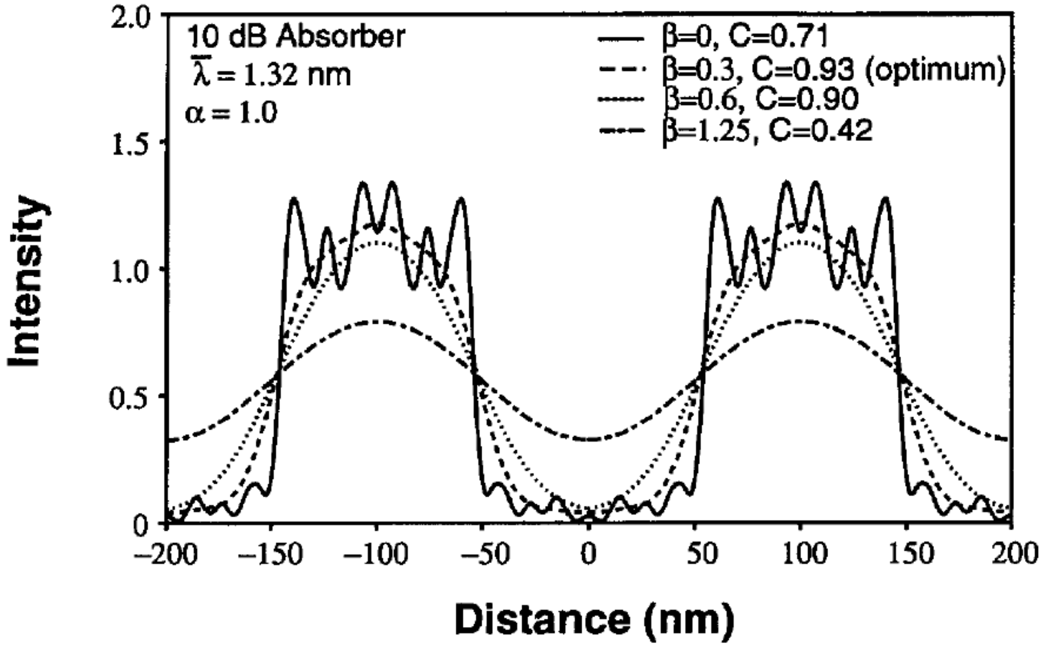


X-ray Lithography

Penumbral Blur: $\delta = sd/D$
Resolution: $W_{min} = (s\lambda/\alpha)^{1/2}$
Typically: $W_{min} = 0.7(s\lambda)^{1/2}$
Coherence: $\beta = \delta/ W_{min}$
Fresnel Number: $\alpha = (s\lambda /W^2)^2$

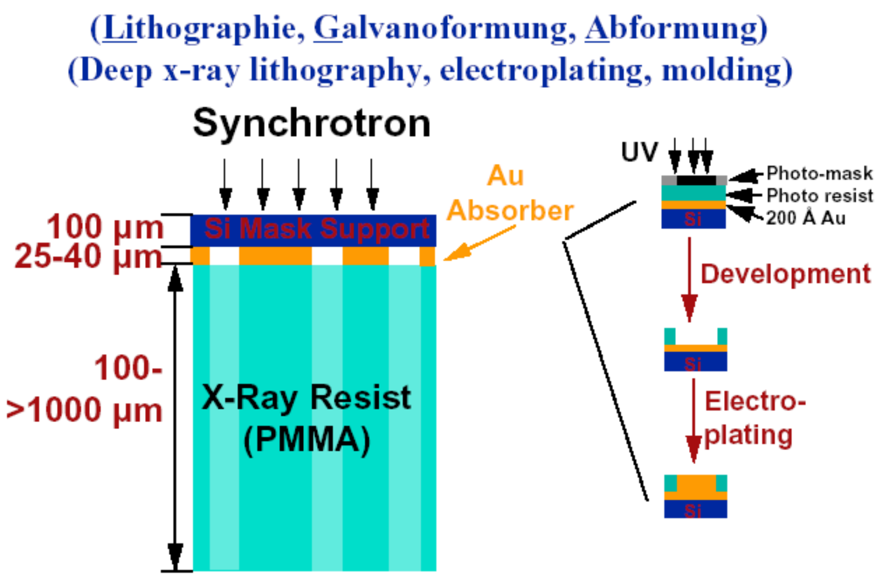
- Resolution limited by wavelength, mask to wafer gap and photoelectrons.
- Essentially free of thin film effects.
- Intrinsincally simple process – difficult in practice.



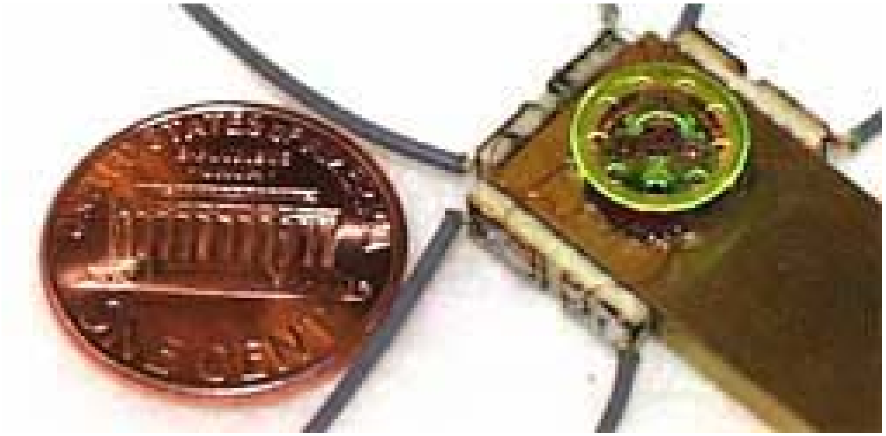


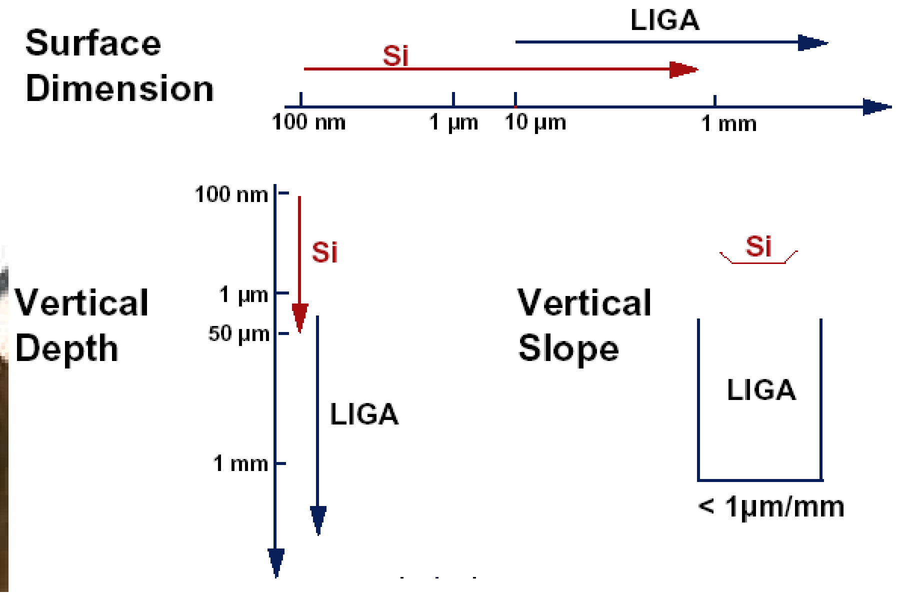
H.I. Smith et al., *Microelectronic Engineering*, **32** 143 (1996)

LIGA



- Limited in resolution but capable of extremely high aspect ratios and very complex shapes



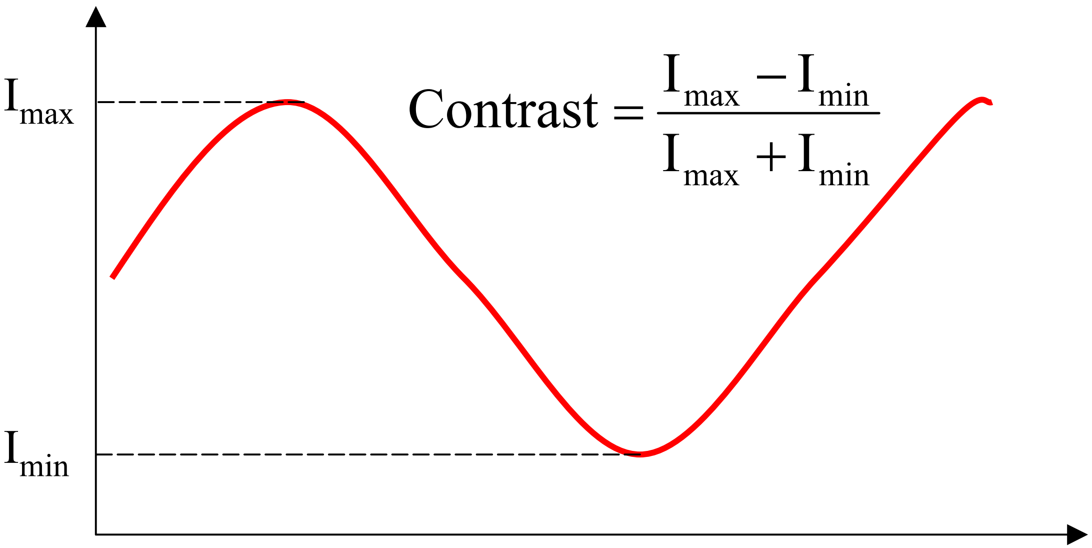


http://www.ca.sandia.gov/liga/index1.html

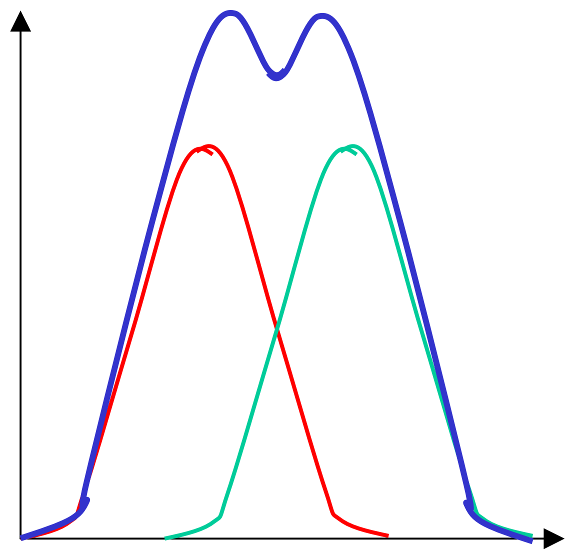
http://www.ca.sandia.gov/liga/pdfs/ligagg.pdf

Imaging in Optical Projection I

- Contrast
- Resolution
  - Depends on required contrast
  - What's required?



$$\text{Contrast} = \frac{I_{max} - I_{min}}{I_{max} + I_{min}}$$

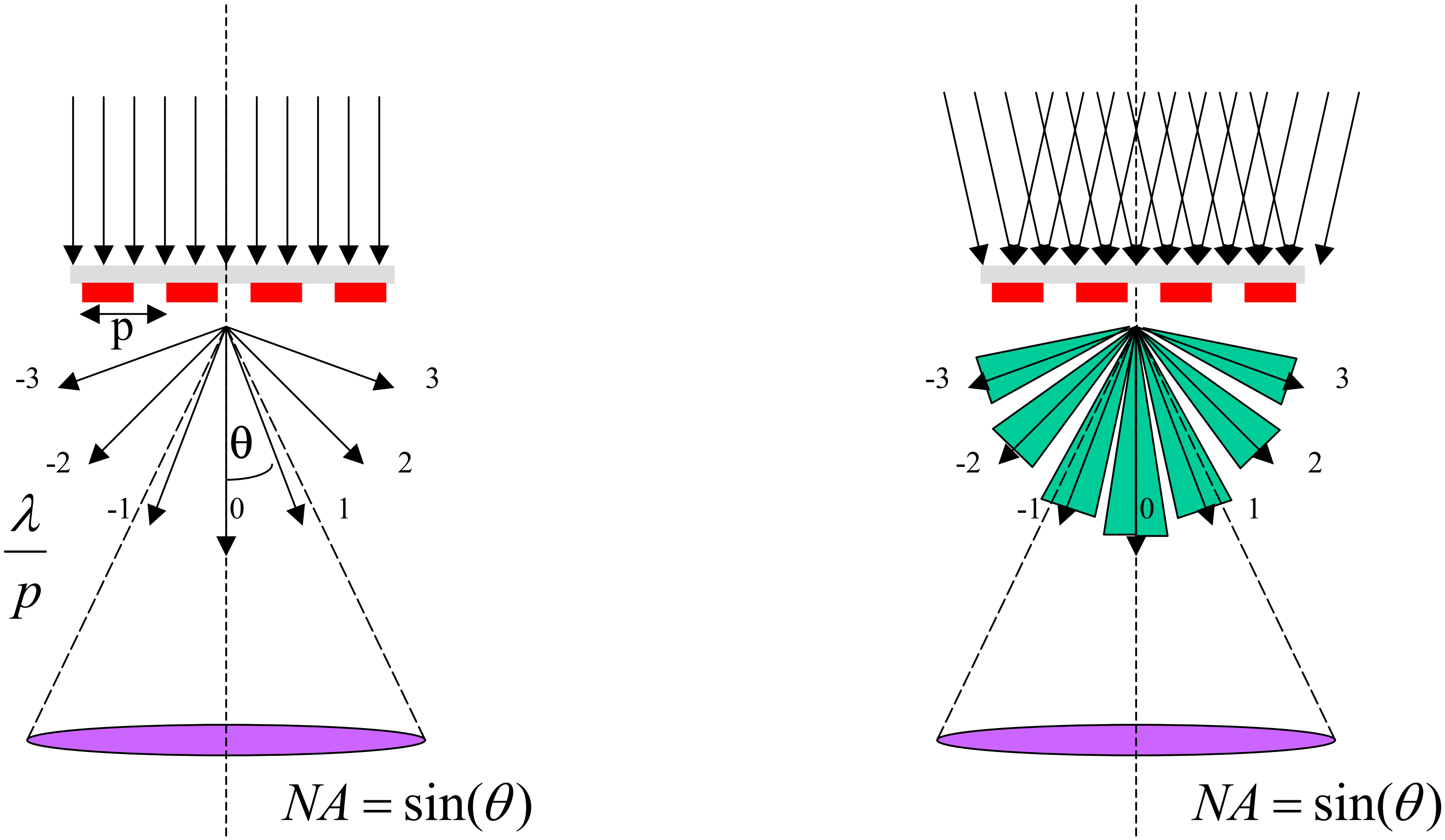


Imaging in Optical Projection II

- Fraunhofer diffraction applies (Source, mask and wafer planes are well separated)
- Mask generates a Fourier transform at the back-focal plane of the objective lens
- Objective lens is finite – inverse transform is imperfect and resolution is degraded
- Resolution
  - $k_1\lambda/NA$
- Depth of Focus (DoF)
  - $k_2\lambda/NA^2$

Coherent vs Incoherent Imaging

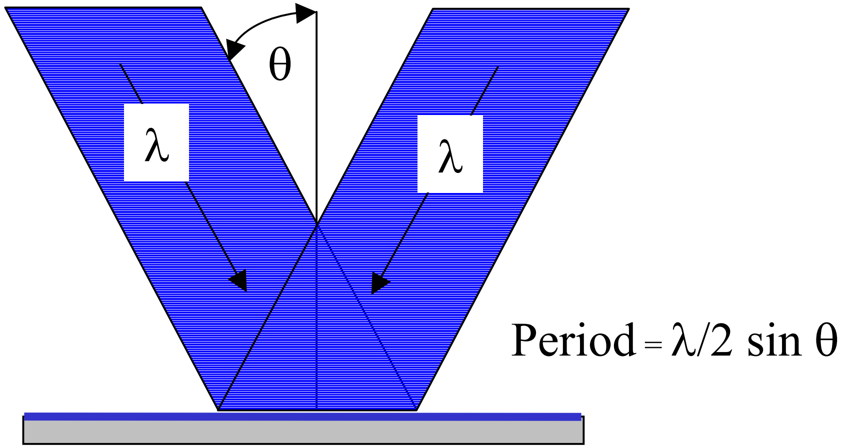
$$\sin(\theta) = \frac{\lambda}{p}$$

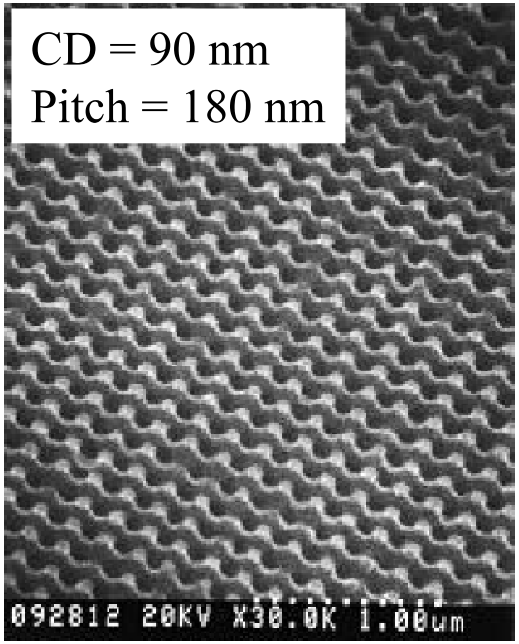


Linewidth d = p/2, Resolution R = 0.5λ/NA

Resolution R = 0.25λ/NA

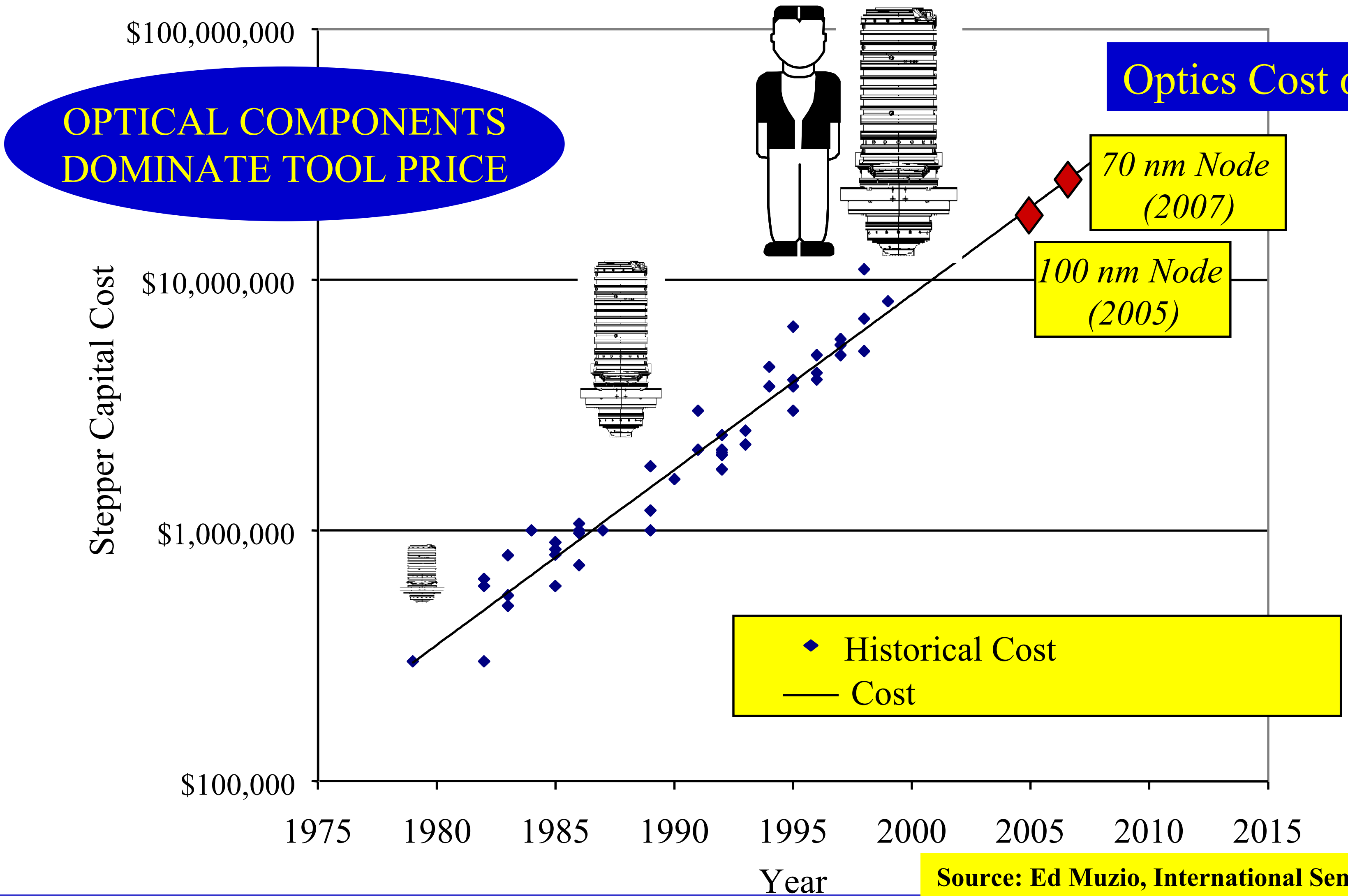
Interferometric Lithography





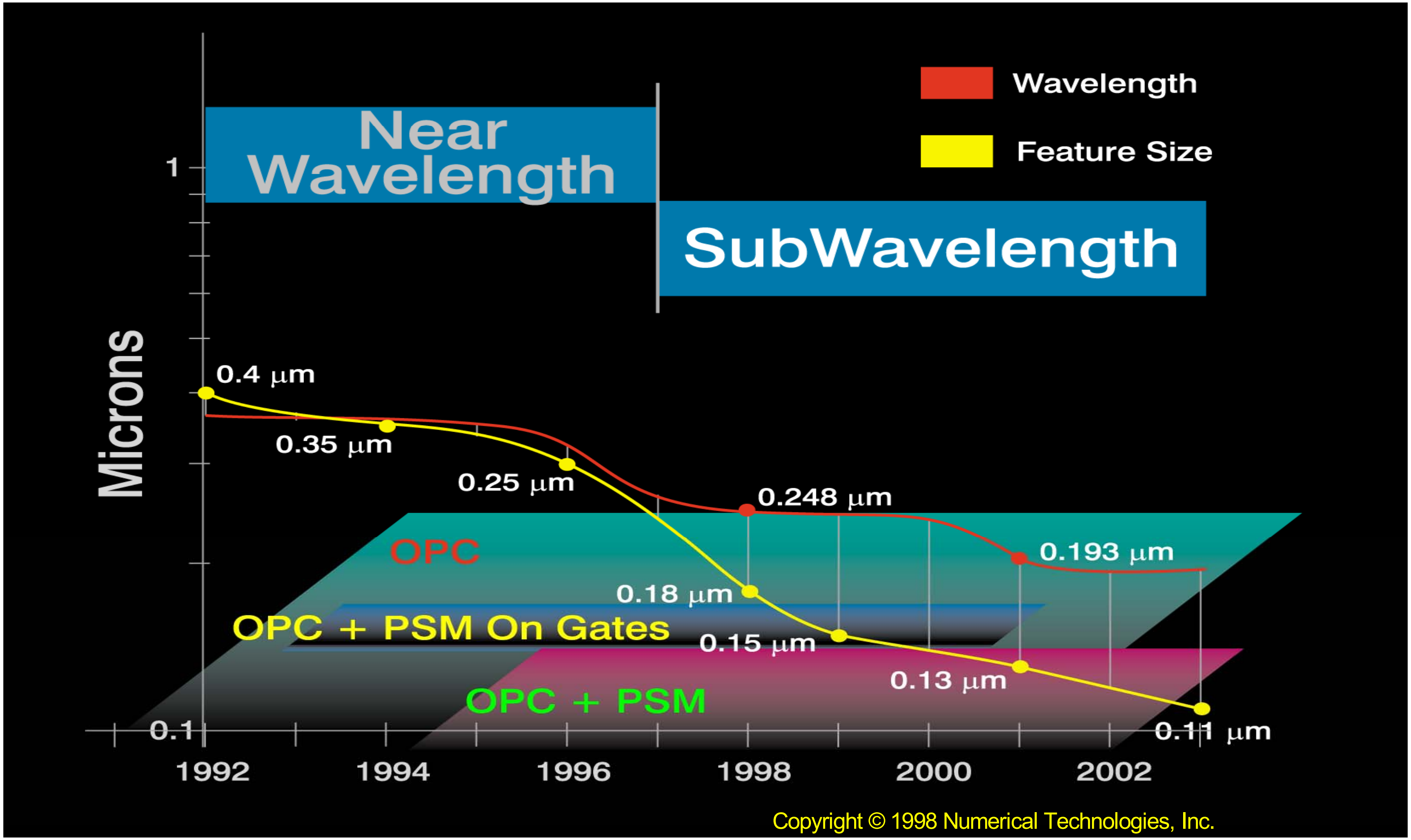
- Capable of patterning large areas with highly spatially coherent features
- Large variety of patterns can be generated using multiple exposures – relies on good resist contrast
- Arbitrary patterns very difficult

Trends in Optical Lithography Cost



Source: Ed Muzio, International Sematech

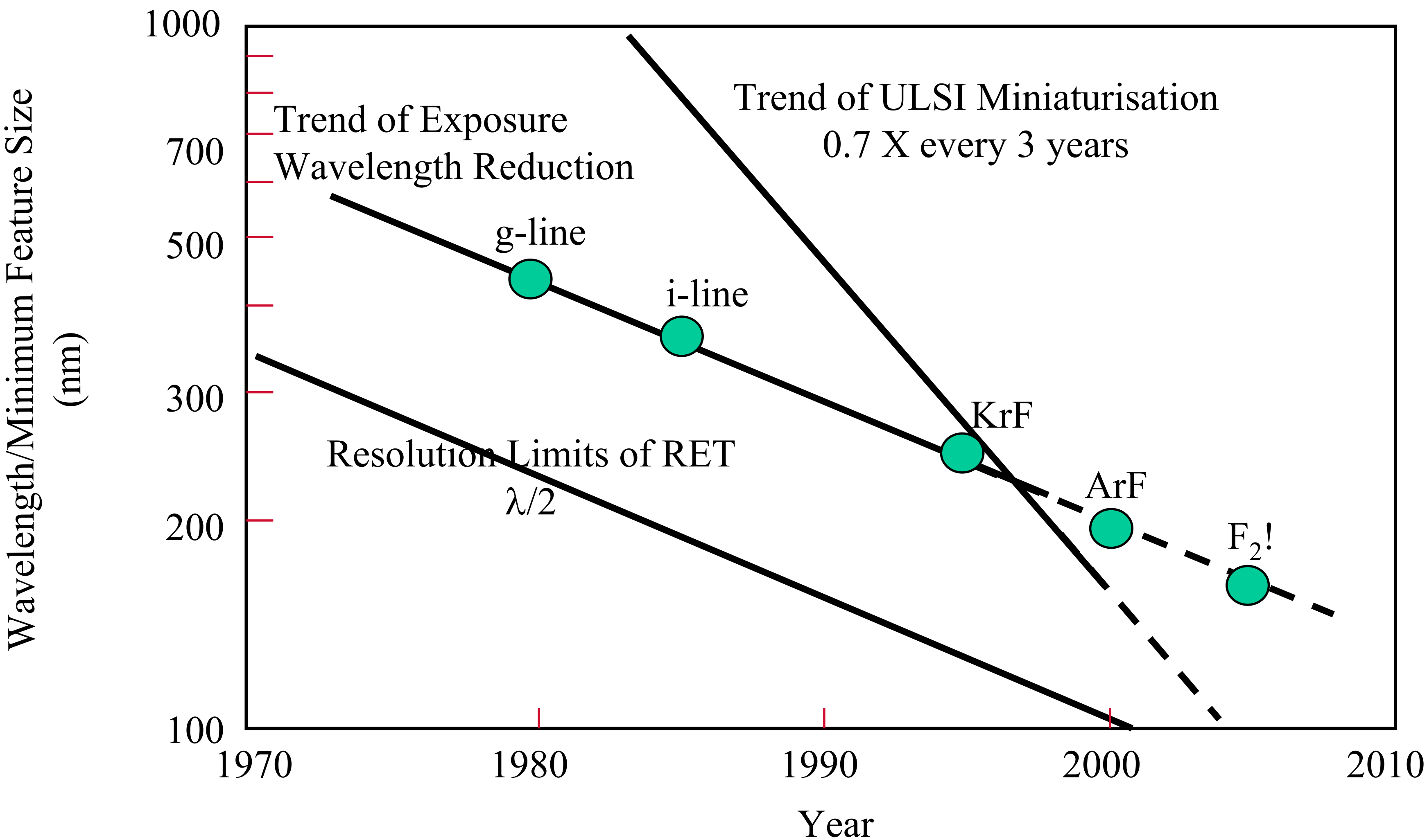
Extending Optical Lithography



"Simulating Fluid Flow Characteristics During the Scanning Process for Immersion Lithography", A. Wei et al., *J.Vac. Sci. Technol. B*, **21** 2788 (2003)

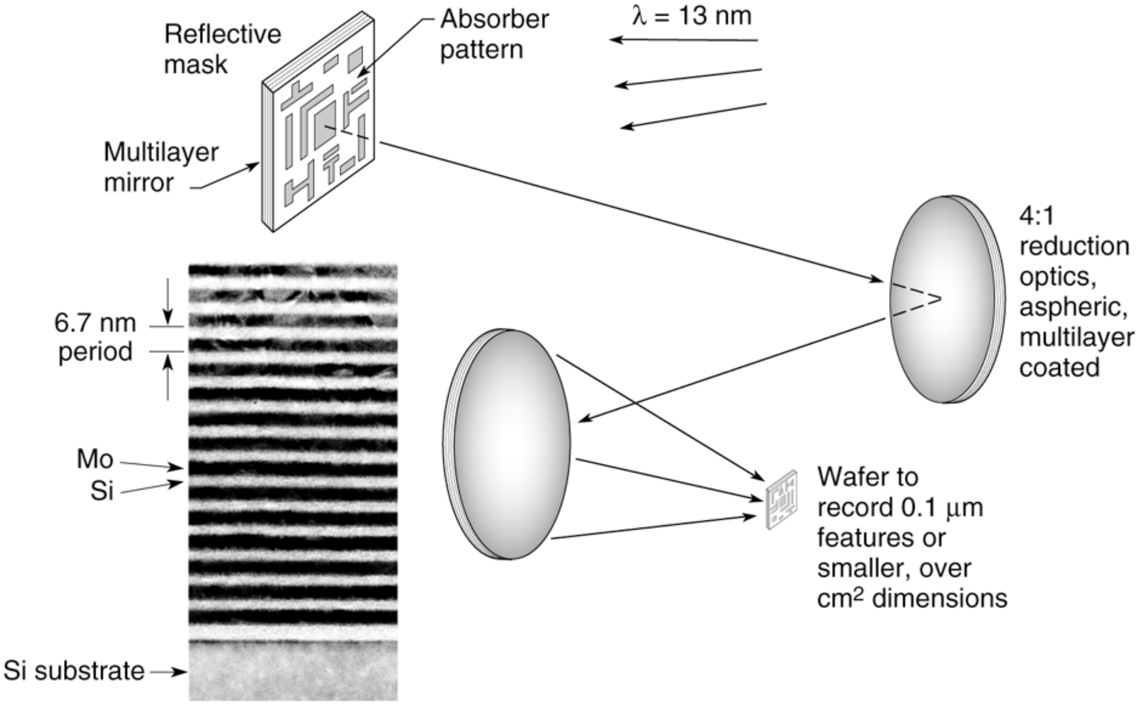
"Extending Optics to 50 nm and Beyond with Immersion Lithography", M. Switkes et al., *J.Vac. Sci. Technol. B*, **21** 2794 (2003)

Wavelength Reduction vs Feature Size Reduction



http://www.research.ibm.com/journal/rd/455/liebmann.html

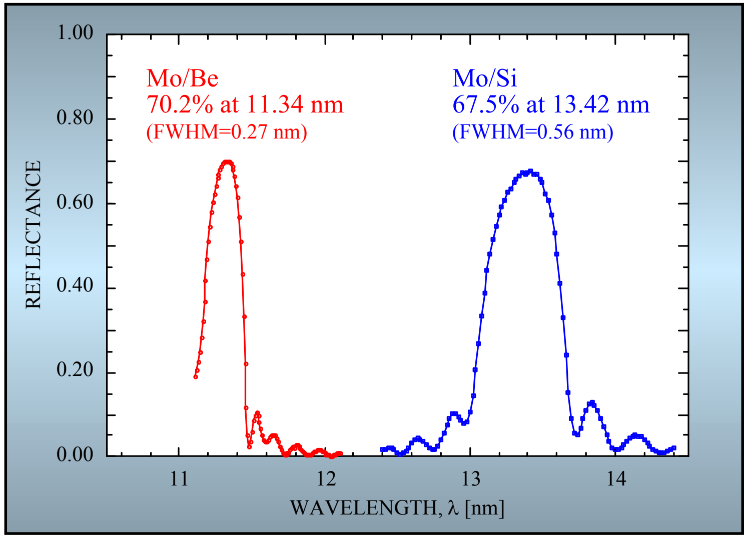
Extreme Ultraviolet Lithography



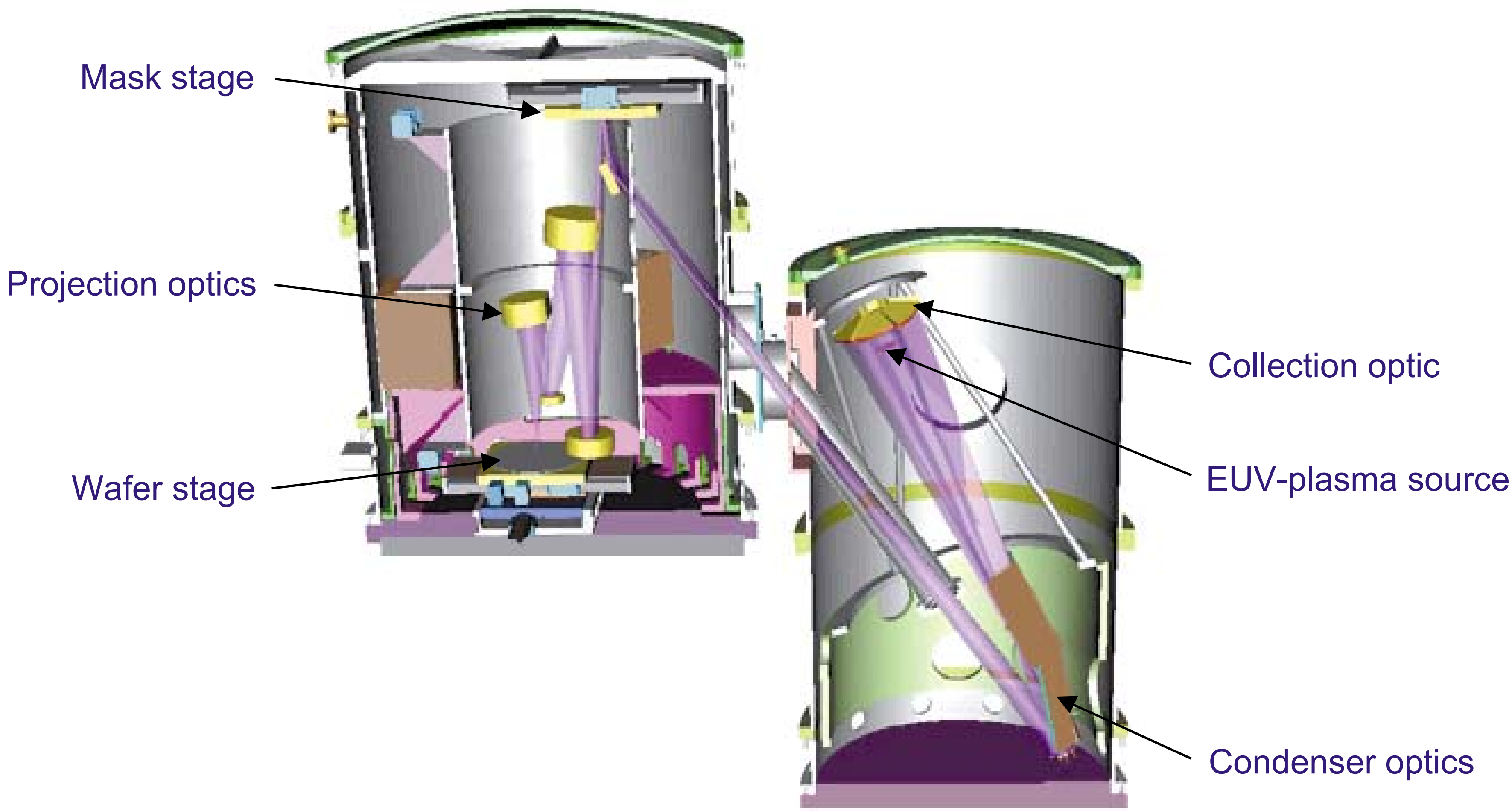
- Short wavelength (13.4 nm) permits high resolution even with small numerical apertures

- Bragg reflector made of alternating Mo/Si layers enables high efficiency (68%) normal incidence reflection of 13.4 nm light

LLNL ML Coating, LBL Metrology

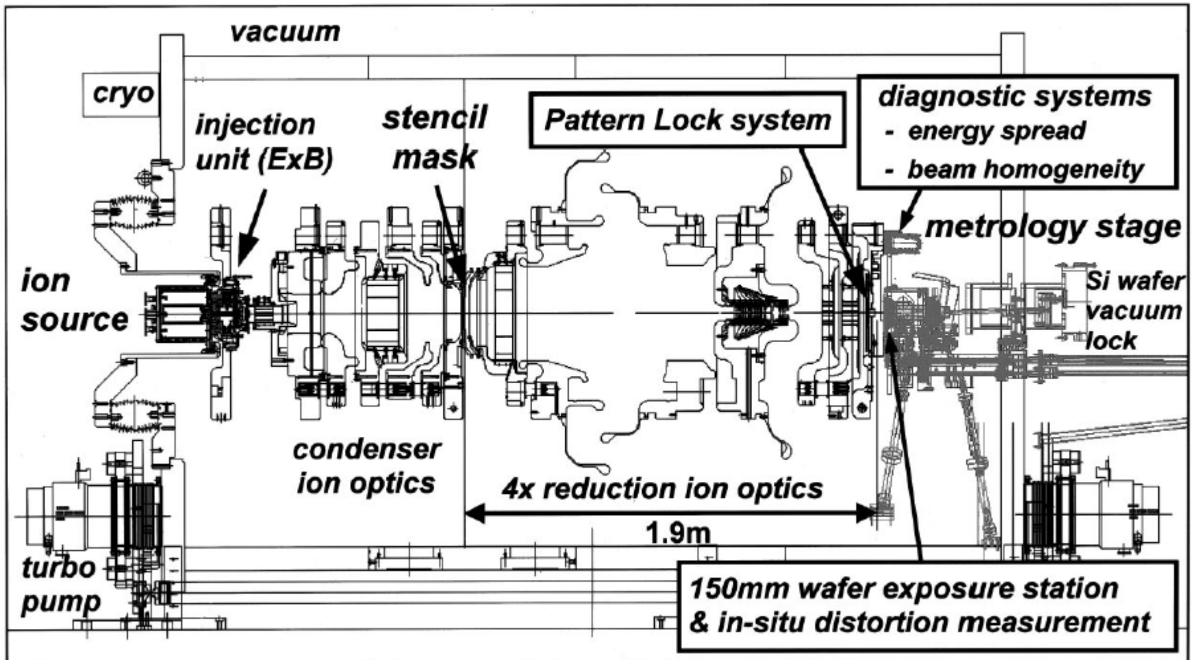


Prototype EUV System

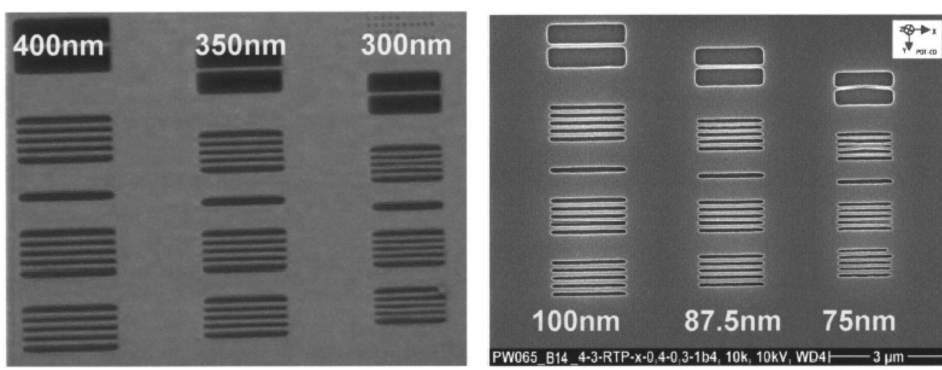


Courtesy: Richard Stulen, Sandia National Laboratories

Projection Ion Beam Lithography



- Potentially very high resolution
- Issues with:
  - Stencil mask fabrication
  - Substrate damage
  - Throughput
  - Stitching/Pattern placement

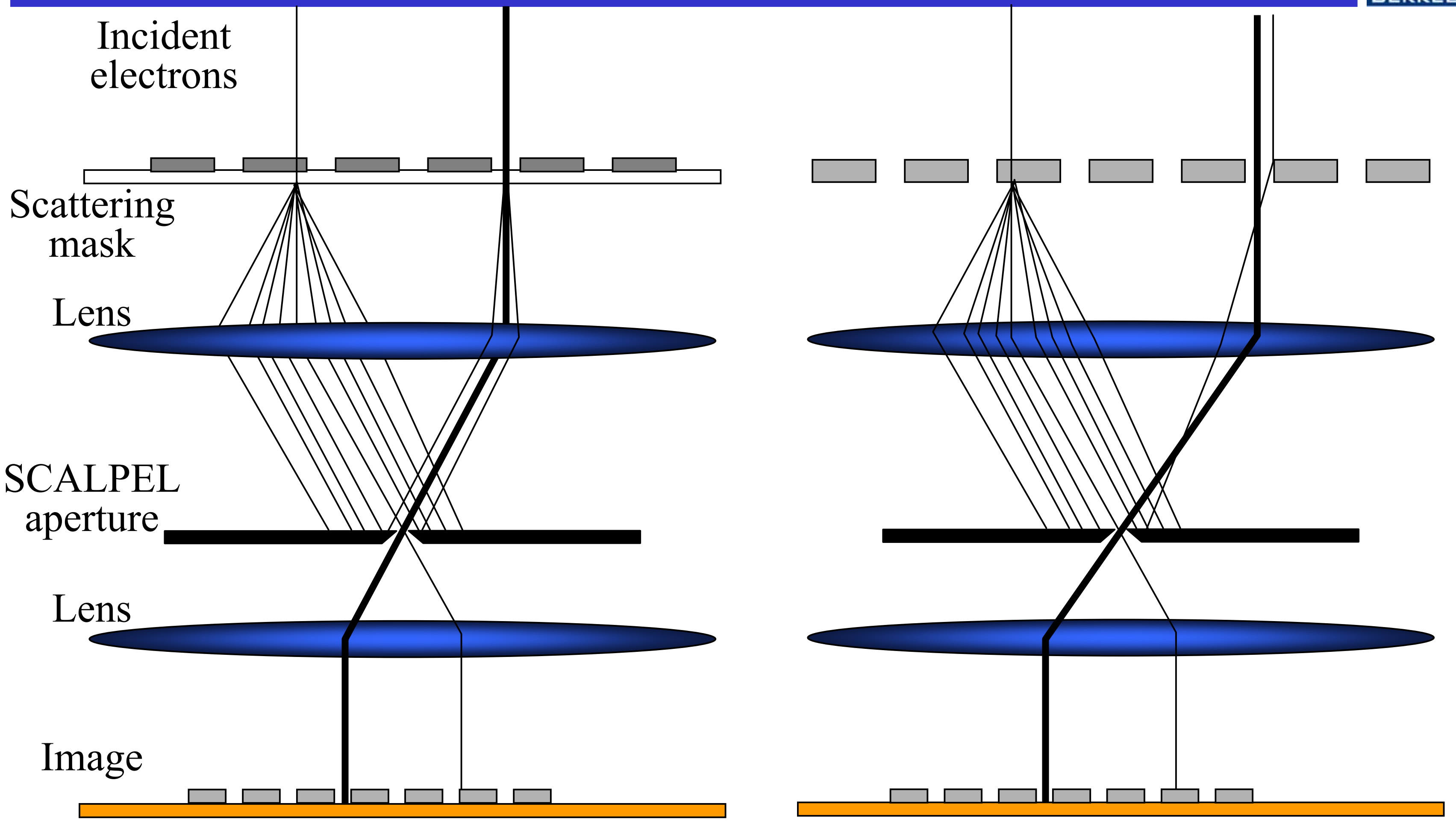


(a) (b)

a) Optical micrograph of a stencil mask and b) corresponding printed image showing 75 nm lines and spaces.

H. Loeschner, G. Stengl, R. Kaesmaier and A. Wolter, *J. Vac. Sci. Technol.*, **B19** 2520 (2001)

SCALPEL Masks - Membrane & Stencil



☞ Dark and light regions differentiated by their scattering strength at the SCALPEL aperture

Extensibility in Lithography

- Although the progress in optical lithography appears to have occurred in discrete steps, progress has, in fact been the result of a very large number of incremental improvements:
  - $R = k_1 \lambda/NA$
  - λ: g-line, i-line, 248 nm, 193 nm, 157 nm

  ations, lens complexity increasing as NA^3

  s NA^3

  ist, CMP

only one adjustable parameter will fail:

meter will fail:

e potential far in advance of the current state-of-the-art and should

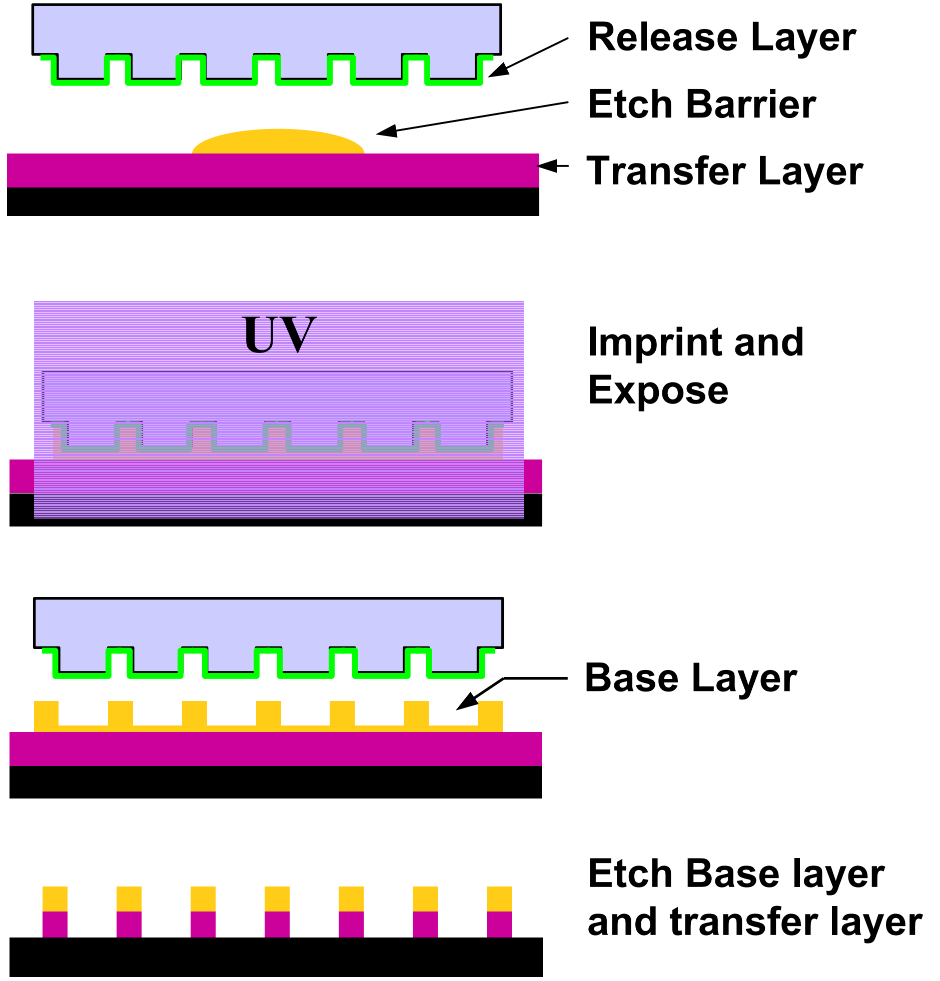
should have many areas where incremental improvements can be

n be made making it inherently extensible

be made making it inherently extensible

Step & Flash Imprint Lithography (SFIL)

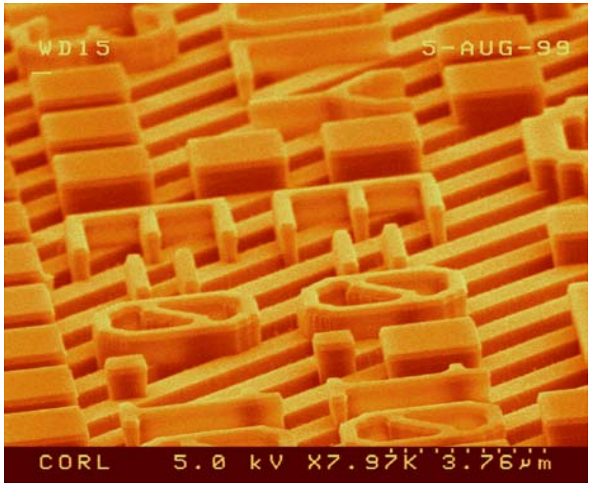
1. Spin coat and cure transfer layer. Dispense etch barrier and position active field under template.
2. Close gap. Illuminate through the template with UV.
3. Separate substrate and template.
4. Etch through base layer and transfer layer, creating high aspect ratio, high resolution pattern on substrate.

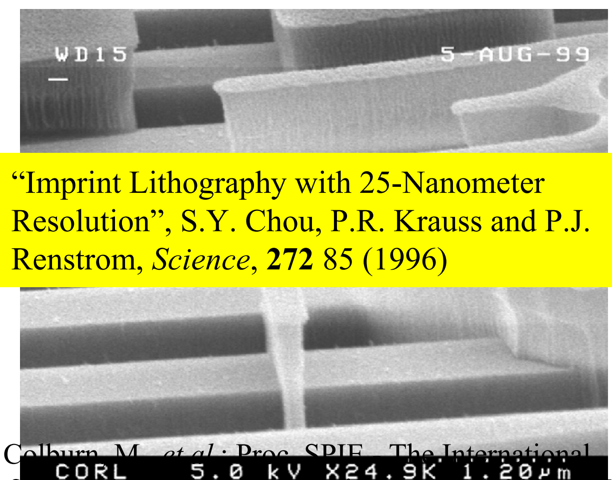


D. J. Resnick, W. J. Dauksher, D. Mancini, K. J. Nordquist, E. Ainley, K. Gehoski, J. H. Baker, T. C. Bailey, S. Johnson, S. V. Sreenivasan, J. G. Ekerdt, and C. G. Willson, SPIE Microlithography Conference 2002

Step & Flash Imprint Lithography (SFIL)

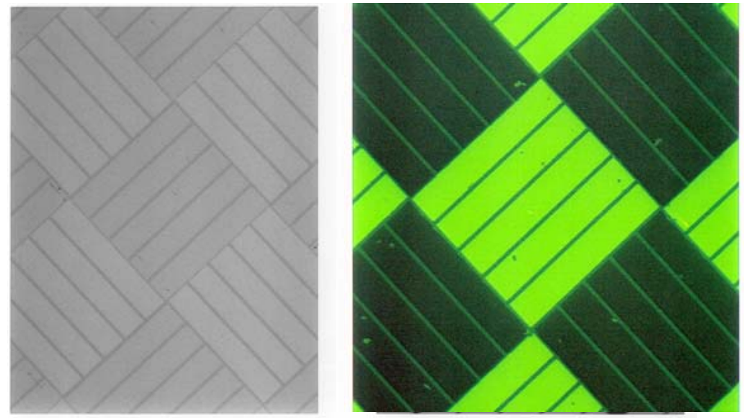
Patterning over topography*



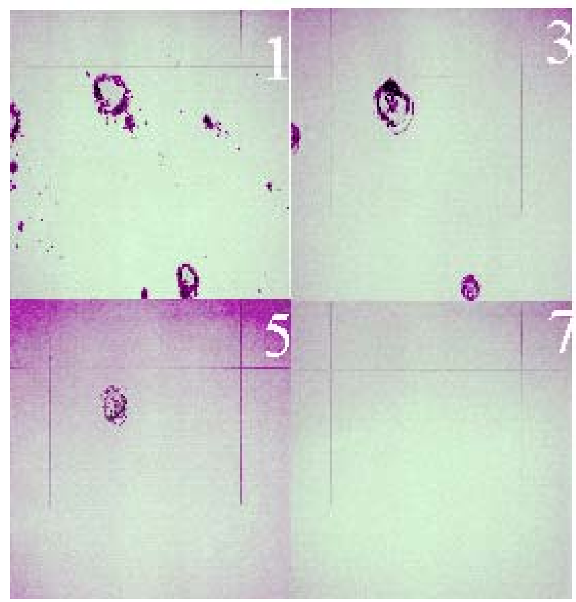


"Imprint Lithography with 25-Nanometer Resolution", S.Y. Chou, P.R. Krauss and P.J. Renstrom, *Science*, **272** 85 (1996)

* Colburn, M., *et al.*; Proc. SPIE - The International Society for Optical Engineering v.3997 (2000) p.453



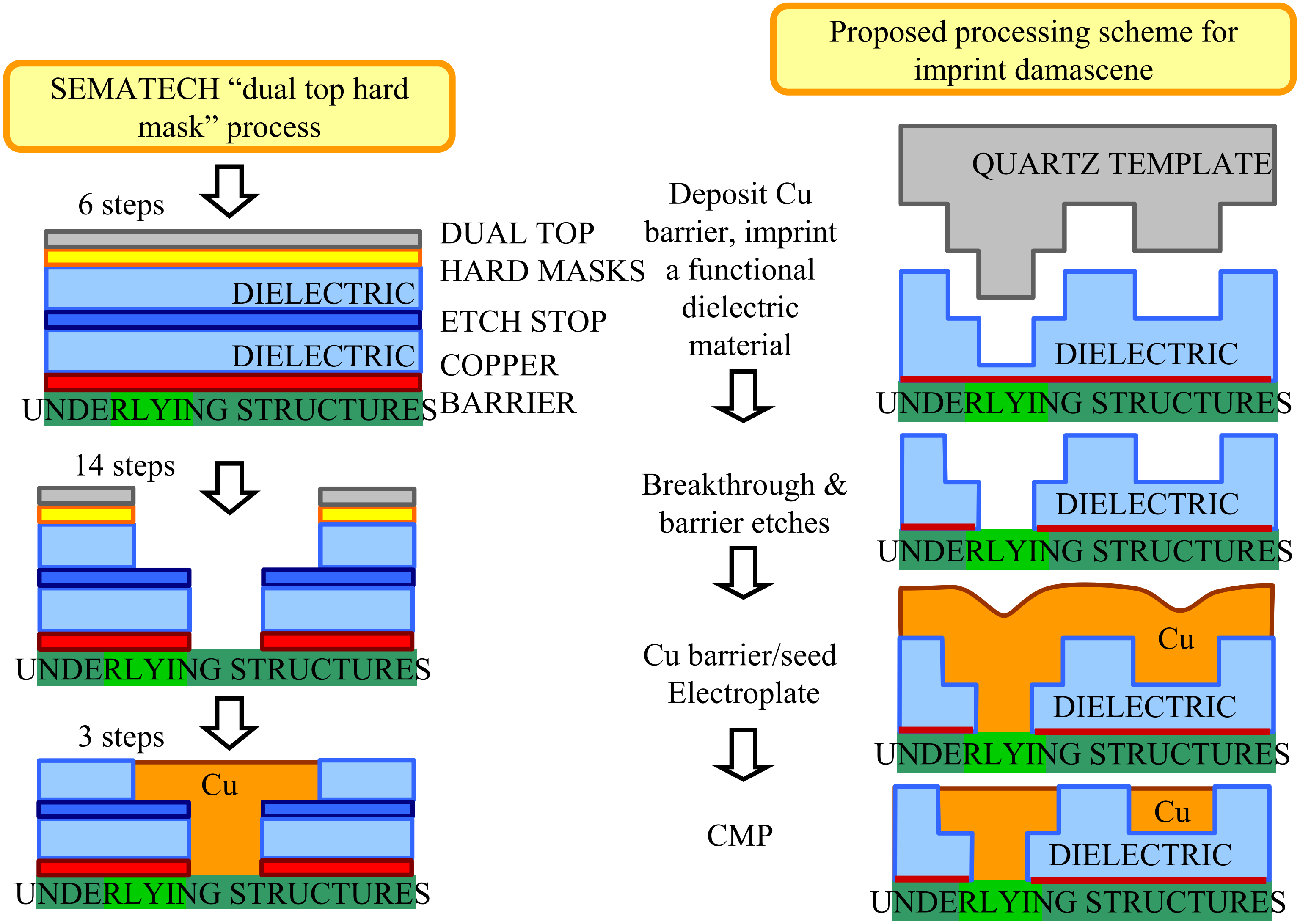
µPolarizer Array*



Self Cleaning effect: Defects initially present on the template disappear after seven imprints

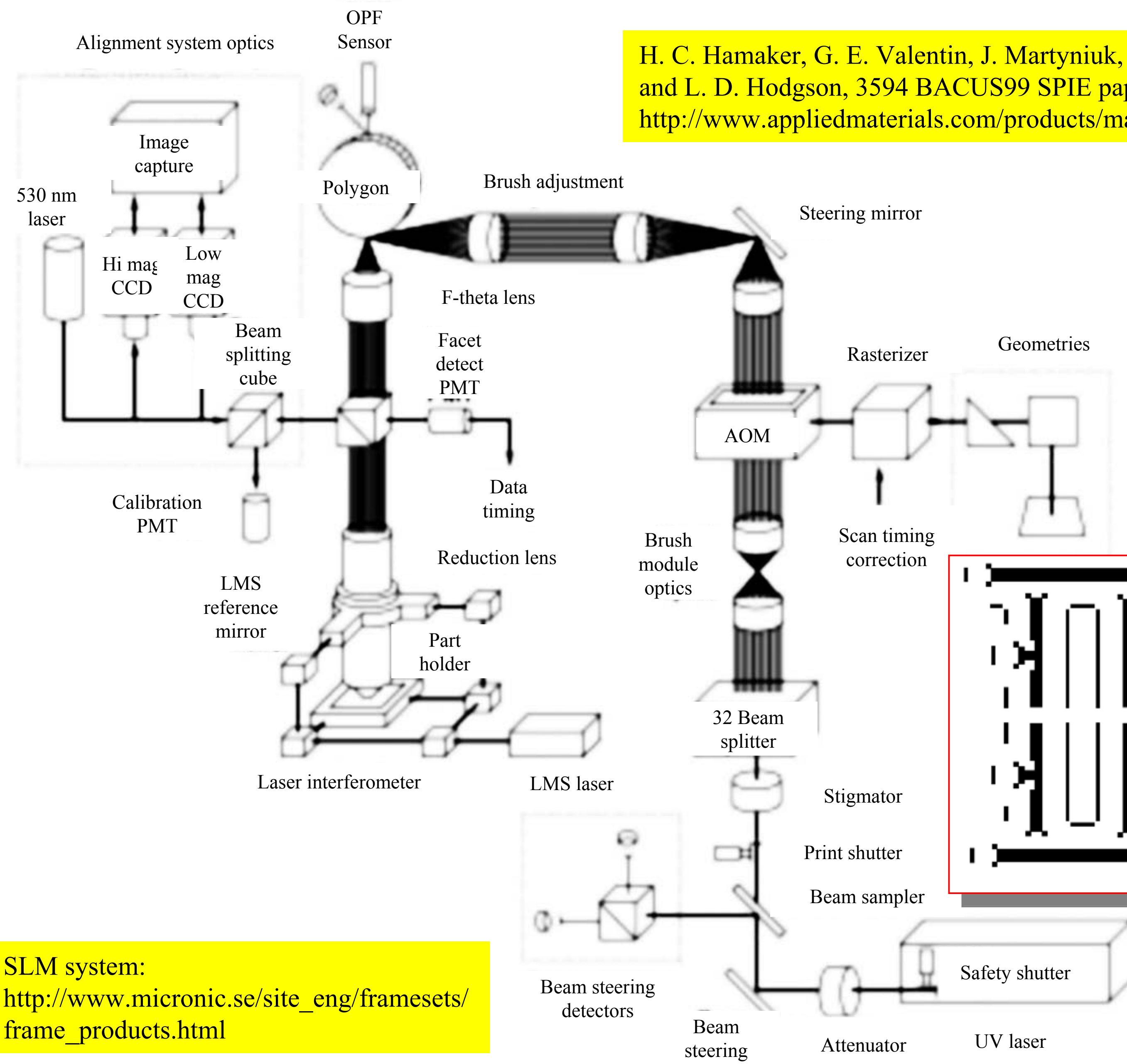
D. J. Resnick, W. J. Dauksher, D. Mancini, K. J. Nordquist, E. Ainley, K. Gehoski, J. H. Baker, T. C. Bailey, S. Johnson, S. V. Sreenivasan, J. G. Ekerdt, and C. G. Willson, SPIE Microlithography Conference 2002

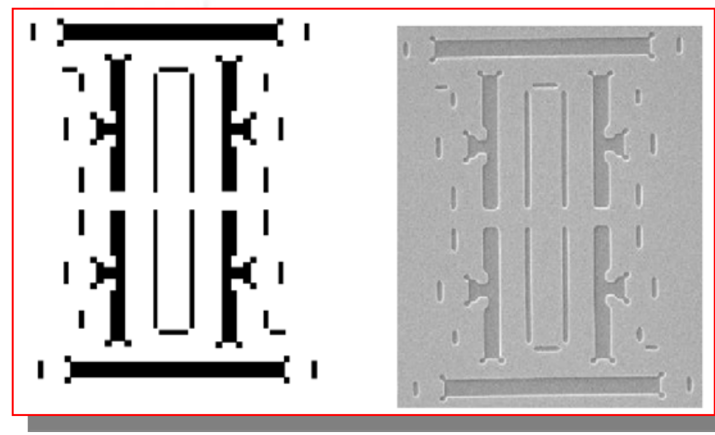
Imprint - why the excitement?



Optical Mask Maker

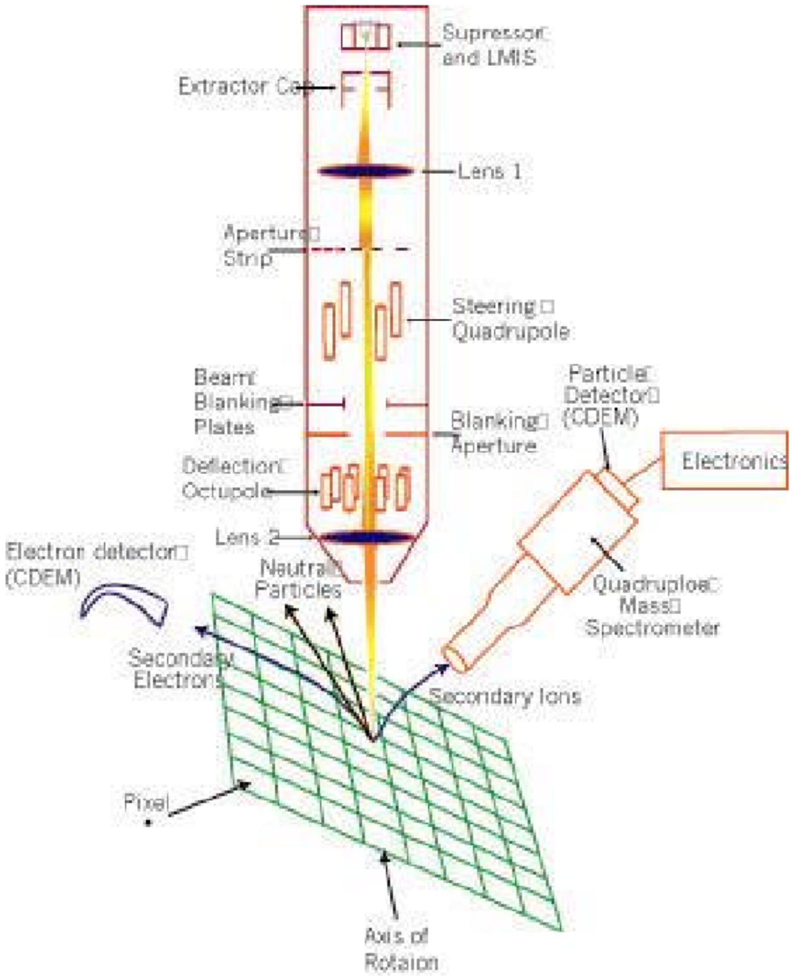
H. C. Hamaker, G. E. Valentin, J. Martyniuk, B. G. Martinez, J. M. Pochkowski, and L. D. Hodgson, 3594 BACUS99 SPIE paper# 3873-06
http://www.appliedmaterials.com/products/mask_technical_papers.html





SLM system:
http://www.micronic.se/site_eng/framesets/frame_products.html

Focused Ion Beam



- Finely focused beam of Ga ions used to sputter or deposit on sample surface
- Beam current 1 pA – 10 nA
- Similar speed issues to direct-write e-beam
- Very versatile for imaging and chemical analysis

Sputtering Yields ~ 1 -10 / incident ion: f (material, θ, E…)

Si ~ 0.5 $\mu m^3 nA^{-1} s^{-1}$ *(E = 30 keV, θ ~ 0º)*

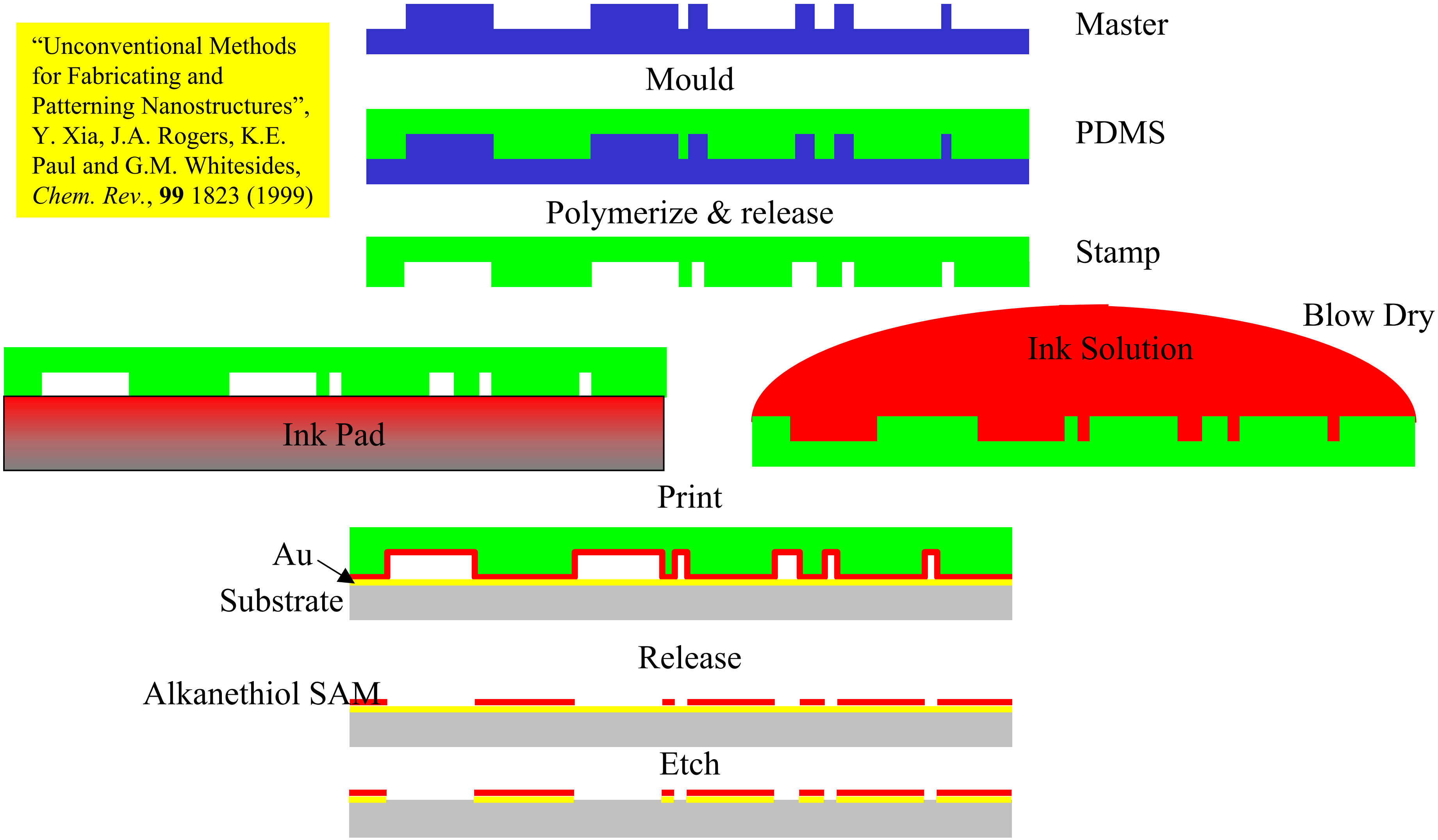
Deposition Yields ~ 1 -10 / incident ion: f (material, θ, E…)

Pt ~ 2 $\mu m^3 nA^{-1} s^{-1}$ *(E = 30 keV)*

D.M. Longo, W.E. Benson, T. Chraska, and R. Hull, *Appl. Phys. Lett.* **78** 981-3 (2001)

MicroContact Printing (μCP)

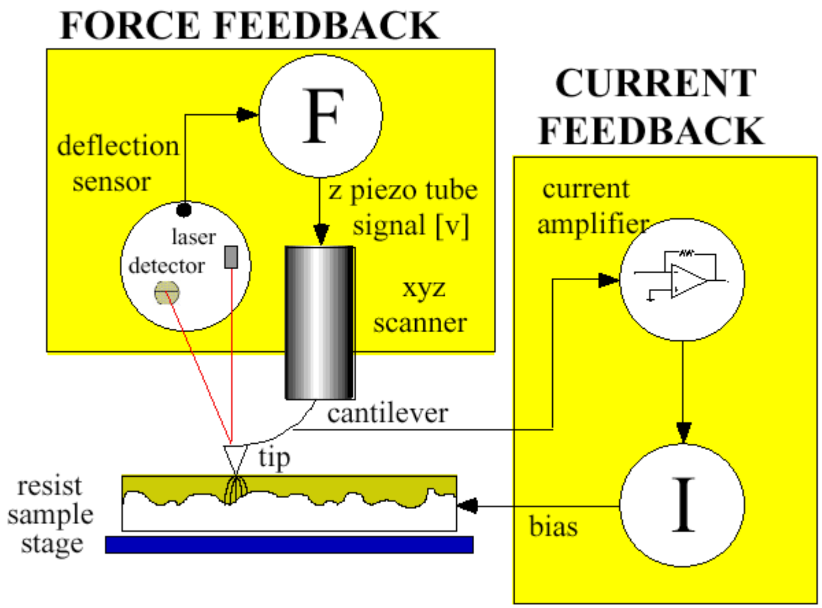
"Unconventional Methods for Fabricating and Patterning Nanostructures", Y. Xia, J.A. Rogers, K.E. Paul and G.M. Whitesides, *Chem. Rev.*, **99** 1823 (1999)

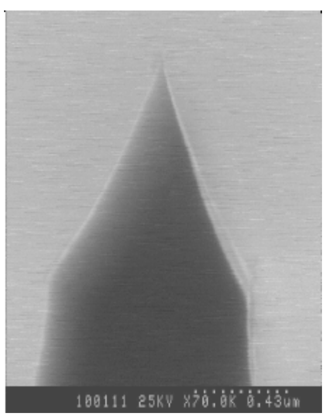


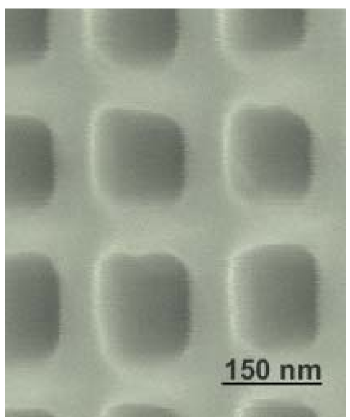
http://www.zurich.ibm.com/st/microcontact/highres/mucp.html

http://gmwgroup.harvard.edu/domino/html/webpage/homepage2.nsf

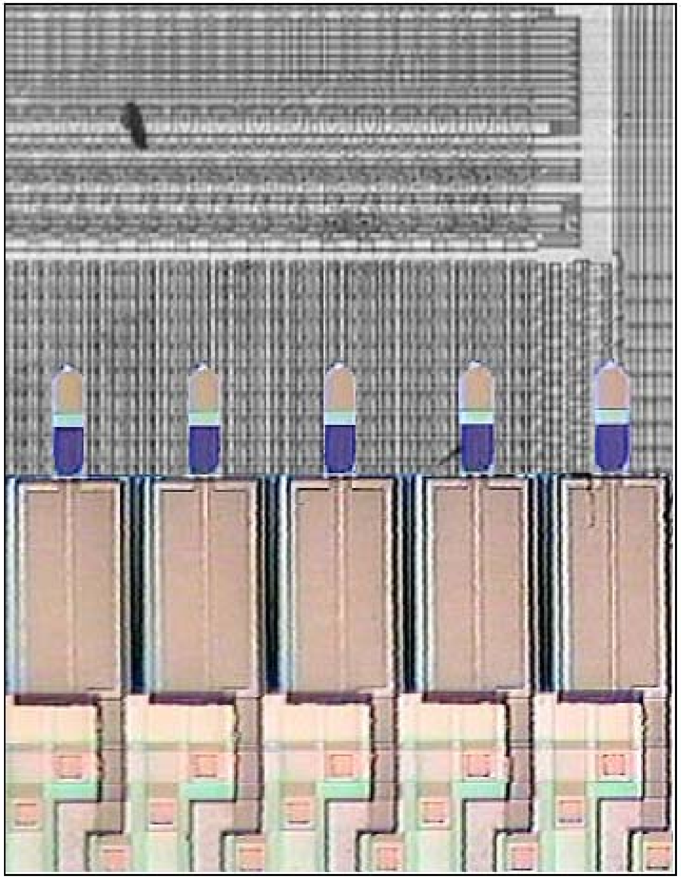
Scanning Probe Lithography







http://www.stanford.edu/group/quate_group

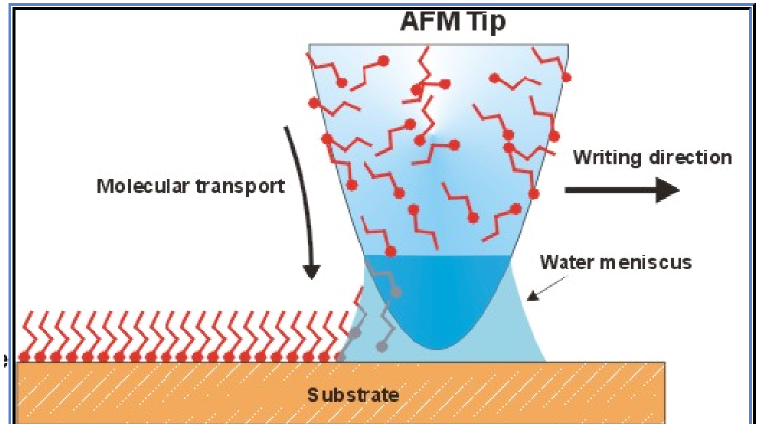


•Goals: 200 mm wafer, 10^{13} 50 nm pixels/wafer, 10 wafers/hr

•Required capabilities: 10 mm/s scan speed, 5 probes/mm^2

S.C. Minne, J.D. Adams, S.R. Manalis, K. Wilder, T. Soh, E. Chow and C.F. Quate, E.L. Ginzton Laboratory, Stanford, Ultra98

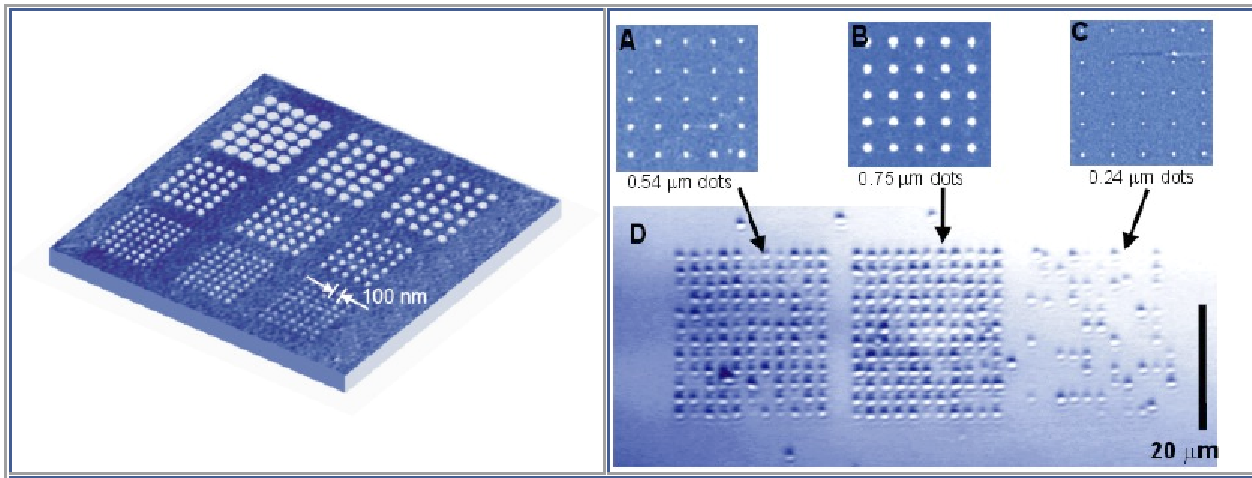
Scanning Probe Lithography - DPN



Dip-Pen Nanolithography: Transport to a surface via a water meniscus.

D. Piner, J. Zhu, F. Xu, and S. Hong, C. A. Mirkin, "Dip-Pen Nanolithography", Science, 1999, 283, 661–63.

- Ability to pattern surfaces with almost any type of chemistry, including sensitive bio-molecules



Left: LFM images of DPN generated charged chemical combinatorial template (white areas are 16-mercaptohexadecanoic acid and dark areas are 18-octadecanethiol) for studying assembly of charged particles. **A, B, and C:** LFM images of MHA template patterns on a gold thin film prior to particle assembly. **D:** an optical micrograph of 930 nm diameter amine-modified polystyrene particles selectively adsorbed to the MHA regions of the substrate.

Ivanisevic, A.; Mirkin, C. A. "'Dip-Pen' Nanolithography on Semiconductor Surfaces," *J. Am. Chem. Soc.*, **2001**, *123*, 7887-7889.

http://www.chem.nwu.edu/~mkngrp/dippen.html